

Mass Outflow in Active Galactic Nuclei: New Perspectives
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HST UV and Keck HIRES Spectra of BALQSOs

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Abstract. In the analysis of broad absorption line (BAL) quasar spectra, Keck HIRES spectra are a useful complement to lower resolution HST and ground based spectra. The HIRES spectra provide accurate parameters for narrow, intervening type absorption systems including Lyman limit systems and a direct measurement of the smoothness of BAL features. The smoothness of the troughs is related to the number of “clouds” in the BAL region if the BAL region consists of clouds. The HIRES spectra, especially for $z \sim 2$ BAL quasars, are also a source of high quality absorption templates. All of the BAL features are apparently resolved in the high resolution spectra ($R \sim 45\,000$), while low resolution ($R \sim 1000$) spectra do not always resolve features belonging to the outflow.

1. Introduction

BALs are present in about 10% of all optically selected quasars (Weymann et al. 1991). The absorption features result from mass outflows with velocity widths of order 2000 to 20 000 km s⁻¹ and maximum velocities to 0.1c and possibly higher in a few cases. The chemical abundances in the BAL regions are of interest as possible indicators of chemical enrichment in galactic nuclei (e.g. Korista et al. 1996, Hamann and Ferland 1999). The absorption features in BAL quasars are not easy to interpret because the BAL region may cover only a part of the background source(s) (Hamann 1998, Arav 1997). Partial covering along the line of sight is common in narrower intrinsic absorbers (e.g. Barlow, Hamann, and Sargent 1997), but more difficult to determine in BAL quasars where the strong doublets of Si IV and C IV are typically blended into wide features. In narrower intrinsic absorption systems, the partial covering is both ion and velocity dependent (Barlow and Sargent 1997). Partial covering definitely influences some narrow BAL components as determined from HIRES observations of CSO 755 (Barlow and Junkkarinen 1994) and Q0226–1024.

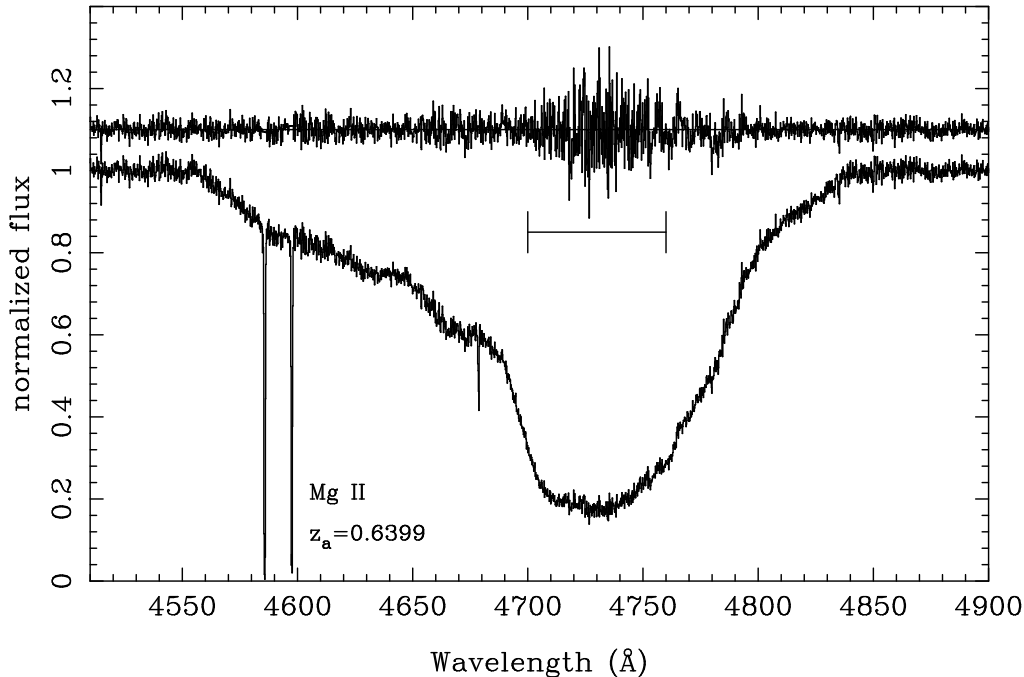


Figure 1. HIRES spectrum, binned 4:1, of the normalized flux in the the C IV BAL in Q1246-057. The rms in the region indicated by the bar (4700 – 4760Å) is discussed in the text.

In this conference proceedings paper, we report on a program that uses Keck HIRES spectra in the analysis of the BALs. BAL features in the UV (observed frame) are analyzed using lower resolution spectra obtained from the HST archive. The HIRES spectra contribute in a number of areas to the analysis. Here we report on: 1.) BAL smoothness, and 2.) absorption templates. As a by-product of the template generation, the the HIRES spectra provide some information on partial covering.

2. Smoothness of BAL Features

The observed smoothness of the BAL features in HIRES spectra rules out a “picket fence” model for the BALs. A “picket fence” model (partial covering by turbulent components in velocity space) was proposed by Kwan (1990) in order to explain the relative weakness of the H I Ly α BAL without resorting to non-solar chemical abundances or partial covering along the line of sight. The smooth BAL features also imply a large number of “clouds” in the BAL region if the BAL region is composed of clouds rather than a smooth outflow.

In order to quantify the smoothness of the BAL features, the C IV BAL in Q1246-047 has been divided by a piecewise polynomial. A small number of polynomials of low order were used to preserve residual fluctuations on scales less than $\sim 200 \text{ km s}^{-1}$. The result of that division is shown in Figure 1. The

entire C IV BAL feature spans absorption velocities from 10 000 km s⁻¹ to 27 000 km s⁻¹.

In the C IV BAL, from 4700 Å to 4760 Å (chosen because the optical depth is roughly constant), there are 375 8.8 km s⁻¹ bins. Each bin is four pixels, about the FWHM resolution for this HIRES spectrum. If we ignore the fact that the bins are not completely independent and also ignore the doublet nature of the C IV transition, an estimate of the number of independent “clouds” can be made from the noise in the divided C IV spectrum. The residual intensity is assumed to be given by $r = e^{-\tau}$ with $\tau = N\tau_c$ where N is the number of clouds contributing to the absorption in each bin and τ_c is the optical depth per cloud. If the clouds obey a simple gaussian distribution with its $N^{1/2}$ rms variation in number, then the rms fluctuations in the divided spectrum, $\sigma^2 = \langle (\delta r/r_s)^2 \rangle$, will be given by: $\sigma \sim \tau \delta N/N = \tau N^{-1/2}$. Here $\delta r = r - r_s$ and r_s is the smooth fit to the data. Putting in the observed $\sigma = 0.059$ and $\tau \sim 1$ in this wavelength range, gives $N \sim 300$ clouds and multiplying by 375 bins gives $N_{total} \sim 10^5$ clouds. This is a very crude estimate, but it is clear that a large number of clouds are needed to make a smooth trough. The residuals observed are at a level slightly higher than expected from the noise estimate in the spectrum ($\chi_\nu^2 = 1.8$, while 1.0 is expected if purely from noise). Given the process of piecing together the HIRES spectral orders, fitting a continuum, and then fitting the trough with a piecewise polynomial, it is possible that all of the observed variation is noise plus some fitting errors.

This analysis is most sensitive to a large number of clouds at the resolution of the observation. Above a few hundred km s⁻¹, for the C IV trough in Q1246-057, some structure is removed by the polynomial fit used to model the smooth trough. The bin size can easily be varied and repeating this exercise shows that for “cloud” (or component) widths from 5 to 200 km s⁻¹ a large number ($\geq 3 \times 10^4$) of clouds is needed. The assignment of a typical velocity width for a typical cloud is uncertain because the physical mechanism behind BAL cloud confinement is not known. Photoionization at parsec distances or greater leads to a much larger number of very small individual clouds and small filling factors (e.g. Junkkarinen, Burbidge, and Smith 1987). Velocity widths ~ 8 km s⁻¹ (FWHM) are produced by thermal broadening for carbon at $T \sim 15$ 000 K, near the temperature expected from photoionization equilibrium.

The smoothness of the troughs in BAL quasars like Q1246-057 may instead indicate a smooth outflow. Models that avoid the need for small clouds have been calculated by Murray et al. (1995). In these models the emission and absorption regions are both formed very close to the central engine (starting point as near as ~ 0.003 pc), and the absorption is produced by a smooth outflow that crosses the line of sight at an angle.

3. Generation of Absorption Templates

The conventional analysis of BAL spectra involves the extraction of absorption templates from the data. Doublets like C IV $\lambda\lambda$ 1548.2, 1550.8 and Si IV $\lambda\lambda$ 1393.8, 1402.8, can be iteratively corrected for the weaker line (Junkkarinen, Burbidge, and Smith 1983) to produce optical depth versus velocity. These templates are shifted to the wavelengths of other transitions and scaled in a χ^2

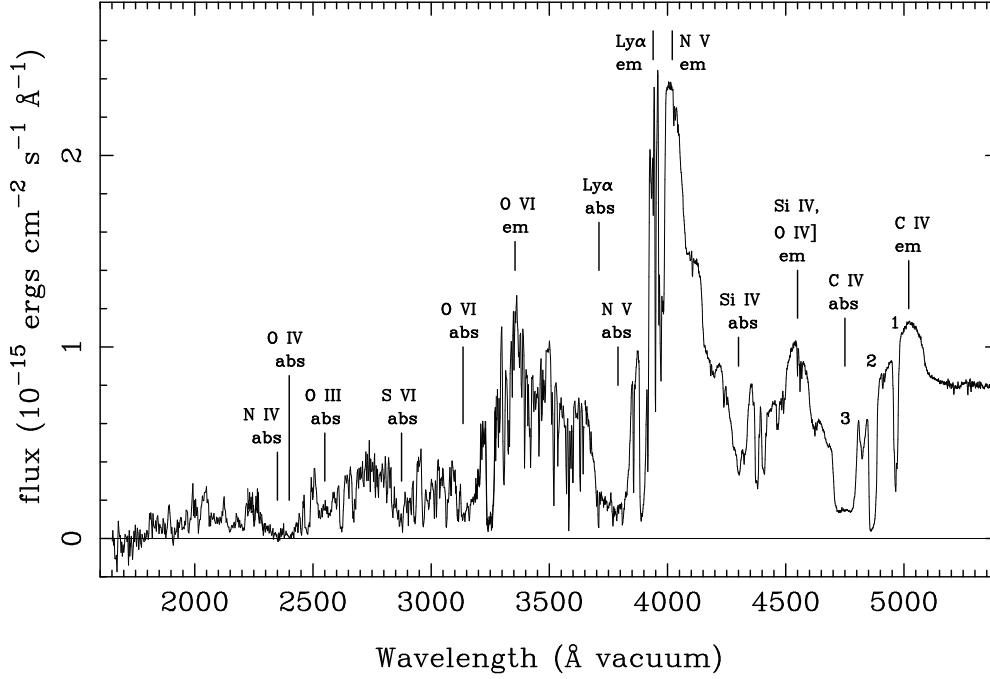


Figure 2. Spectrum of Q0226-1024. The UV HST/FOS spectra were obtained on 1991 June 13 with the G270H grating and 1992 July 25 for the G190H grating. The HST spectra have been smoothed using 8:1 binning for the G190H and 4:1 binning for the G270H. The optical spectrum was obtained on 1996 October 9 with the Lick 3m.

fitting procedure to match the data and give approximate (lower limit) column densities (e.g. Korista et al. 1992). Because BAL quasars like Q0226–1024 (Fig. 2) and Q1246–057 have smooth troughs with no apparent features at scales around 30 km s^{-1} , spectra obtained at the HIRES resolution (typically $7 - 9 \text{ km s}^{-1}$ FWHM) can be smoothed to produce high quality templates.

Figure 3 shows the C IV and Si IV absorption templates extracted from our Keck HIRES spectrum of Q0226–1024. The spectra were smoothed to produce these templates and could be further smoothed without losing any of the apparent structure. At the HIRES resolution of 7 km s^{-1} FWHM for Q0226–1024 and at a resolution of 9 km s^{-1} FWHM for Q1246–057 the troughs are completely resolved. The troughs are not without structure as is illustrated in the case of Q0226–1024. The lowest velocity BAL feature (marked “1” in Figs. 2 & 3) breaks up into three “spikes” of absorption repeated in both C IV and Si IV. These features are not resolved with $R \sim 1000$ spectra.

Analyzing BAL quasar spectra using multiple templates that cover only a part of the velocity space may be possible when the BALs occur in clumps well separated in velocity. Troughs 1 and 2 in Q0226–1024 are narrower than the Si IV $\lambda\lambda 1393.8, 1402.8$ doublet. Trough 2 shows partial covering in Si IV with $C_f \approx 0.70$ based on measurements of the doublet using: $C_f = \frac{I_1^2 - 2I_1 + 1}{I_2 - 2I_1 + 1}$, where

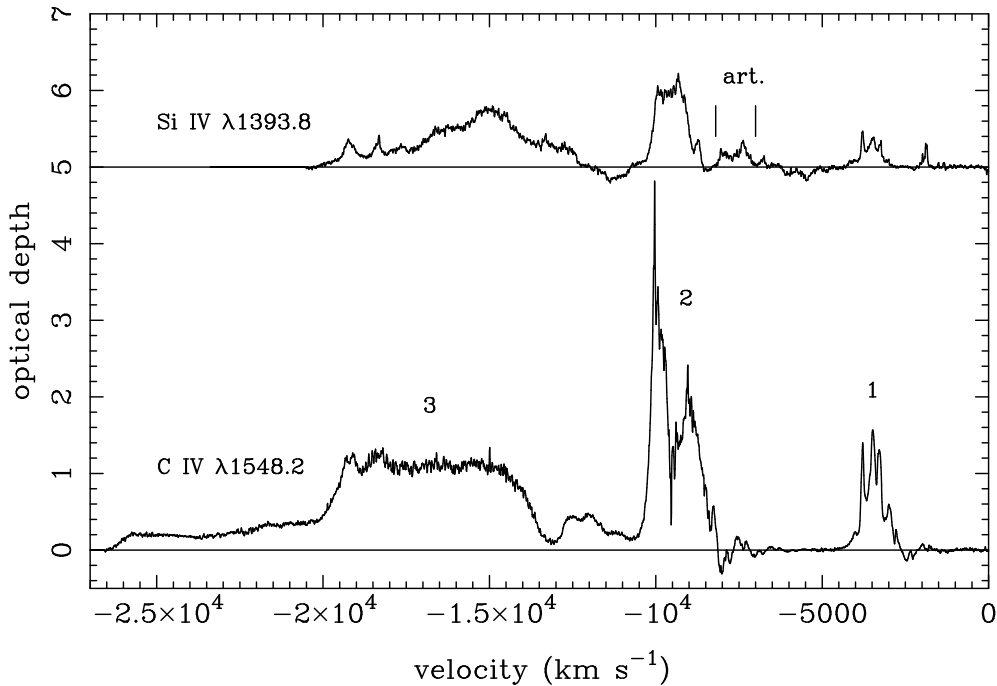


Figure 3. Q0226-1024 absorption templates for C IV and Si IV extracted from a Keck HIRES spectrum smoothed to 18 km s^{-1} FWHM.

I_1 and I_2 are the residual intensities in the stronger and weaker lines in the doublet (e.g. Hamann et al. 1997). The template extraction procedure assumes full covering and produces a false absorption feature around 7500 km s^{-1} in the extracted template (marked “art.” Fig. 3). Such weak, echo-like features and regions where the template goes negative are indications that the assumption of complete coverage of the background source has broken down. Artifacts can also be produced by a poor choice of continuum, so the templates must be evaluated allowing for some uncertainty in the continuum. For very wide features with smooth edges compared to the doublet separation, like trough 3 in C IV in Q0226–1024, it is easy to construct partial covering models that mimic the data. The data are consistent with either 100% covering over those velocities or with high optical depths and a covering function that is chosen to produce the shape of the observed feature. The important issue of partial covering dominating the shape of the broad BAL troughs is not one that is easily resolved.

4. Summary

The BALs in Q1246–057 and Q0226–1024 are found to be smooth and completely resolved in the Keck HIRES spectra at a resolution of $7 - 9 \text{ km s}^{-1}$ FWHM. The smoothness of the C IV trough in Q1246–057 leads to an estimate of at least 3×10^4 clouds (or components) of width 5 to 200 km s^{-1} comprising the deepest part of the trough. Keck HIRES spectra are a good source for generating absorption templates for analyzing lower resolution ground based

and HST UV spectra of BAL quasars. The spectrum of Q0226–1024 shows BAL features with structure that is not resolved in low resolution spectra. The Q0226–1024 Si IV template also shows artifacts produced by a breakdown of the assumption of complete covering of the background source. In broader BAL features (broad relative to the doublet separation), the effects of optical depth and partial covering are not easy to separate. Spectropolarimetry (e.g. Cohen *et al.* 1997) or photoionization equilibrium analysis could yield estimates of the partial covering and the true column densities in the broad features.

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